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"DETERMINATION OF CONSTITUTIVE EQUATIONS FOR TITANIUM ALLOYS APPLICABLE TO SHEET METAL FORMABILITY"

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ABSTRACT

A program to determine constitutive equations applicable to the sheet formability of the titanium alloy Ti-6Al-4V has been initiated. Load relaxation tests have been conducted at temperatures from 25° to 500°C over a strain-rate range of 10^{-2} to 10^{-8} sec^{-1} using a programmable digital data acquisition system. The relaxation data, presented as log stress vs. log strain-rate hardness curves, illustrate the dependence of the strain-rate sensitivity, an important sheet metal formability index, on strain rate and temperature. The shapes of the hardness curves agree qualitatively with those predicted by the mechanical equation of state suggested by Hart. In particular, the transition from low temperature to high temperature grain matrix deformation behavior is clearly observed. Anomalous curvatures, apparently due to a strain aging mechanism, were observed in some room temperature hardness curves at low strain rates.

1.0 Summary of Results

1.1 General Background and Objectives

The formability of sheet metal is dependent upon certain plastic properties of the material identified as formability indices. These affect formability in two distinct ways. First of all they determine whether the sheet can provide the state of strain required by the process without an intervening failure. In addition, they affect the way strain is distributed in the sheet during forming and, hence, partially determine the maximum strain that will be imposed. The most important sheet formability indices are the strain hardening coefficient and the strain-rate sensitivity. These affect both limit strains and strain distribution and, hence, correlate with successful forming in most sheet processes. Other properties such as the flow stress, plastic strain anisotropy ratio, and certain fracture strains also enter the formability analysis for a limited number of processes and materials.

Recently, Thomas, Gegel, and Teutonico [1] presented a systematic approach to assessing sheet metal formability based upon analytical material constitutive equations and calculated forming limit curves. The forming limit curve (FLC), which gives the locus of principal strains beyond which failure is expected, is based on a specific failure mode and corresponding set of material properties. The constitutive equation is used to input these properties, including their dependence on strain, strain-rate, and temperature, into the FLC analysis. When combined with numerical sheet metal process simulation models, an integrated CAD/CAM program for sheet metal forming could be developed.

The first analytical FLC to be calculated [1,2] was based on a plastic instability failure criterion valid in the tension-compression biaxial

strain quadrant, namely Hill's condition [3] for the formation of a localized neck. The constitutive equations used described the strain hardening behavior but neglected strain rate sensitivity. Work is continuing to incorporate rate sensitivity into this analysis. This is a difficult step since an analytical solution is being sought. However, it is now commonly recognized that rate sensitivity is as important as strain hardening capacity for good formability. This has been demonstrated, for example, by the numerical FLC of Marciniak [4] and the punch-stretching experiments of Hecker [5]. One additional result of the analytical approach [1] using the Hill condition has been to show that, if rate sensitivity is to be included, the constitutive equation cannot be separable into factors which depend on strain and strain rate only, such as $\sigma = P(\varepsilon)\ Q(\dot{\varepsilon})$. In this case, the rate dependence drops out of the FLC. This provides an additional restriction on the form of a usable constitutive equation.

The overall requirements for material constitutive equations applicable to sheet metal formability have led us to the mechanical equation of state approach developed by E. W. Hart [6]. This is a flow theory in which the flow stress is expressed as a function of strain rate, temperature and one or more explicitly history-dependent parameters which characterize the current structure of the material. An important feature of this approach is that the two most important formability indices, the strain rate sensitivity and the strain hardening coefficient, appear as state functions such that their dependence on stress, strain rate, and temperature can be specified. The history-dependent structure parameters partially determine the current mechanical properties and can be used, for example, to describe lot-to-lot variations. Strain hardening can be described in terms of the evolution of these structure parameters with

accumulated strain.

At intermediate temperatures, experiments on a variety of materials [7] have shown that a single parameter called the plastic hardness σ^* characterizes the metallurgical microstructure. At constant temperature, σ^* orders a one-parameter family of curves usually plotted as log σ vs. log $\dot{\varepsilon}$. Each of these "hardness" curves provides a unique, history-independent measure of the current mechanical state of the material. The slope of the hardness curve is simply the strain-rate sensitivity $\nu(\sigma,\dot{\varepsilon})$. The hardness curves are obtained from load relaxation data. The advantages of this test are that it can sample a wide range of strain rates and, since the plastic strain accumulated during the test is usually small, represents a specimen with nearly constant structure.

An analytical form for the mechanical equation of state has recently been proposed by Hart [8], namely

$$\sigma = \sigma^* \exp\left[-\left(\frac{\dot{\varepsilon}^*}{\dot{\varepsilon}}\right)^{\lambda}\right] + \sigma_o\left(\frac{\dot{\varepsilon}}{\dot{\alpha}}\right)^{1/M} . \qquad (1)$$

This equation represents non-elastic grain matrix deformation only with the first term describing thermally-activated flow and the second term describing dislocation glide. The parameters λ and M are material constants and σ^*, $\dot{\varepsilon}^*$, and σ_o $(\dot{\alpha})^{-1/M}$ represent the current mechanical state. The equation should be applicable at all temperatures below about 0.45 T_M where grain-boundary sliding must also be considered.

For typical relaxation test strain rates, approximately 10^{-8} to 10^{-2} sec^{-1}, the flow stress during relaxation is usually above σ^* for $T < 0.3$ T_M. In this case Eq. (1) can be approximated as

$$\sigma = \sigma^* + \sigma_o\left(\frac{\dot{\varepsilon}}{\dot{\alpha}}\right)^{1/M}, \qquad (2)$$

and the hardness curve is concave upward. At temperatures above 0.3 T_M (but below 0.45 T_M), Eq. (1) can be approximated by its first term

$$\sigma = \sigma^* \exp \left[-\left(\frac{\dot{\varepsilon}^*}{\dot{\varepsilon}} \right)^{\lambda} \right], \tag{3}$$

and the hardness curve is concave downward. These curvatures can be used to distinguish low temperature and high temperature behavior.

In the work described here, load relaxation tests have been used to initiate a study aimed at determining the range of conditions for which a constitutive equation based on a small number of history-dependent parameters can be determined for the alpha/beta titanium alloy Ti-6Al-4V. Relaxation tests have been conducted between room temperature (0.15 T_M) and 500°C (0.40 T_M). The resulting hardness curves illustrate the dependence of strain-rate sensitivity on strain rate, stress, and temperature. Constant extension rate tests for determining strain hardening behavior and tests to typical sheet forming temperatures of 750°C (0.53 T_M) are being carried out in a follow-on program sponsored by the Air Force Materials Laboratory.

1.2 Material Selection

The experimental tests were performed on two different grades of Ti-6Al-4V, standard and ELI. Both were supplied in the annealed condition, according to specification MIL-T-9047, as centerless-ground round bar with diameters of 11.4 mm and 13.2 mm respectively. The chemical analyses provided by the suppliers are listed below in Table 1.

Table 1. Chemical Analysis in Weight Percent

Ti-6Al-4V	Al	V	Fe	C	H	O	N	Ti
Standard	6.2	4.0	.14	.03	.0086	.164	.015	bal.
ELI	6.2	4.05	.15	.013	.0045	.10	.011	bal.

Button-head tensile specimens with a guage diameter of 4.52 mm and a nominal guage length of 20 mm were machined from the bar. Room temperature tensile tests were conducted at a crosshead speed of 12 mm/min. (nominal strain rate = 10^{-2} sec^{-1}) on two "standard" specimens and one "ELI" specimen to determine typical mechanical properties. These are listed in Table 2.

Table 2. Typical Mechanical Properties

Ti-6Al-4V	F_{ty}(MPA)	F_{tu}(MPA)	TE(%)	RA(%)	EU(%)
Standard	938	1057	20.2	47.8	4.6
ELI	831	965	18.4	53.1	3.5

Metallographic specimens were prepared to examine the transverse (to the rod axis) cross-section of each material. Photomicrographs are shown in Fig. 1. The microstructure of the standard grade Ti-6Al-4V consists of equiaxed alpha, some acicular alpha, and a small amount of intergranular beta phase. The microstructure of the ELI grade Ti-6Al-4V consists of a fine dispersion of beta within the alpha matrix.

1.3 Development of the Automatic Data Acquisition System

In order to conduct load relaxation tests over a strain-rate range of 10^{-8} to 10^{-2} sec^{-1}, it is necessary to use a digital data acquisition system for the load-time data. This allows sufficiently rapid data acquisition at the highest strain rates and provides for the necessary resolution at the lowest strain rates where the load is decreasing very slowly.

The data acquisition system which we have developed is based on a DEC PDP 11/05 minicomputer interfaced to an HP 3480B/3484A digital voltmeter. An ASR33 Teletype (TTY) is used for data output. Although the DVM is cap-

able of 1000 readings per second, use of the PDP 11 internal line frequency clock set the maximum reading rate at 60 per second. The digital interface coupling the PDP 11 to the DVM was designed and constructed in the Physics Department at Wright State University for another project and was available at the start of this Grant period. However, the necessary software had not been completed.

The program which we developed to control the DVM reading sequence is outlined in the flow chart shown in Fig. 2. The main program accepts a data sequence matrix, starts the line clock, provides access to the interrupt routines, and determines the data output format. Each line clock pulse (60 Hz) transfers control to the line clock interrupt routine. If a new DVM reading is called for, a second interrupt routine can set the DVM function, range, and filter. A third interrupt routine then triggers the DVM reading. During the portion of the 1/60 second interval that this reading sequence is not occurring, the main program controls data output to the TTY. Since the data is temporarily stored in a buffer, the reading rate is not limited by the maximum TTY rate.

To run the program for a particular experiment we input a data sequence matrix. Each row specifies a number of readings, a specific time interval (in units of 1/60 sec.), and a filter setting. The range and function are preset at 10 VDC. Up to 20 such rows can be specified. At the end of the matrix, the program calls for one additional data sequence row. This is used for unloading after a relaxation experiment. We believe that this system represents a unique application of computerized data acquisition to the mechanical testing of metals.

1.4 Load Relaxation Test Results

Load relaxation tests were carried out on the Ti-6Al-4V tensile

specimens described in sec. 1.2 using an Instron 1123 tester. For each run, the specimen was loaded into the plastic region at a nominal strain rate of 10^{-2} sec^{-1}. During loading and the initial relaxation, load readings were taken at a rate of 10 per second. The data sequence matrix provided for this rate to be reduced incrementally. Each run lasted for 4 to 5 hours, and the final load reading rate was usually one per 100 seconds. The load relaxation tests were carried out at room temperature, 200°C, 350°C, and 500°C. For the high temperature tests, the temperatures were maintained by a resistance tube furnace and a high stability 3-mode Eurotherm controller which held the specimen temperature constant to within 0.25°C. The load-time data was processed by a computer routine which calculated true stress σ, true strain rate $\dot{\varepsilon}$, and strain-rate sensitivity ν at a subset of the load readings separated by approximately equal load increments. The routine also produced log σ vs. log $\dot{\varepsilon}$ hardness curve plots.

Load relaxation runs were conducted on four standard grade specimens and one ELI grade specimen at room temperature. Either two or three runs were conducted on each specimen at different plastic strain levels.

Hardness curves for three runs conducted on a single standard grade specimen at true strains of .015, .051, and .088 are shown in Fig. 3. The three curves are generally concave upward and essentially parallel, illustrating the typical low temperature behavior predicted by Eq. (2). The strain rate sensitivity ranges from about 1.2×10^{-2} at the highest strain rates down to about 0.8×10^{-2}. However, the hardness curves at the two highest strains do show some anomalous curvature below approximately 10^{-5} sec^{-1}. This may be a strain aging effect.

In conducting multiple relaxation runs on a single specimen, reloading yield points were observed. These are illustrated in Fig. 4 where the

load-displacement curves for initiating the three relaxation runs of Fig. 3 are compared to an uninterrupted load-displacement curve for a different specimen. Similar reloading yield points were observed during the tests on the ELI grade specimen. Reloading yield points have also recently been reported by Guimaraes and Meyers [9] in commercial purity titanium and by Saleh and Margolin [10] in β-Ti-Mn. These letter authors attribute the effect to dislocation pinning by vacancies upon unloading.

The initial hardness curves on all five specimens tested at room temperature are shown in Fig. 5. The lowest curve is for the ELI grade specimen and is parallel to the hardness curves for the standard grade specimens in spite of their different microstructures. Again, the hardness curve for the specimen at the highest strain level shows the anomalous curvature at low strain rates.

Multiple load relaxation runs were also conducted on standard grade specimens at 200°, 350°, and 500°C. In addition, successive relaxation runs were conducted on a single standard grade specimen at 500°, 350°, and 200°C. The hardness curves for these runs are shown in Fig. 6 and illustrate clearly the transition from high to low temperature behavior. The 500°C (0.40 T_M) hardness curve has the shape predicted by Eq. (3) with the strain-rate sensitivity varying from 1×10^{-2} to 24×10^{-2} at a strain rate near 10^{-6} sec^{-1}. The 350°C (0.32 T_M) hardness curve shows the transition between high and low temperature behavior. The strain rate sensitivity goes through a minimum at a strain rate near 10^{-5} sec^{-1}. At 200°C (0.24 T_M), the relaxation behavior represents the low temperature regime.

In summary, hardness curves derived from load relaxation data for annealed standard grade Ti-6Al-4V at temperatures between 25° and 500°C agree qualitatively with those predicted by the analytical form (Eq. (1))

suggested by Hart [8]. The transition from low temperature to high temperature grain matrix deformation behavior is clearly observed. Limited data on a second microstructure (ELI grade) suggest little variation in the rate sensitive behavior. Anomalies apparently due to a strain aging mechanism complicate interpretation of the hardness curves at room temperature at strains near the maximum uniform strain especially in tests involving reloading. Work is continuing to fit Eq. (1) to the hardness curves and explain the variations in hardness with strain and temperature.

1.5 List of References

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10. Y. Saleh and H. Margolin, "Reloading Yield Points in β-Ti-Mn Alloys," presented at the TMS-AIME Fall Meeting (1977) and private communication.

1.6 List of Figures

1. (a) Microstructure of annealed Ti-6Al-4V; (b) Microstructure of annealed ELI Ti-6Al-4V.

2. Flow chart of the automatic digital data acquisition system control program.

3. Room temperature hardness curves for a standard grade Ti-6Al-4V specimen at plastic strains of .015 (▲), .051 (⊖), and .088 (◆).

4. Load-displacement curves (solid lines) for the three relaxation runs of Fig. 3 showing reloading yield points in comparison to the uninterrupted load-displacement curve (dashed line) for a different specimen.

5. Initial room temperature hardness curves for an ELI-grade specimen at a plastic strain of .013 (▲) and four standard grade specimens at strains of .007 (⊖), .015 (◆), .018 (+), and .033 (✱).

6. Hardness curves for a single standard grade specimen at temperatures of 500°C (▲), 350°C (⊖), and 200°C (◆).

2.0 Coupling Activities

The purpose of this Grant, which was funded through the AFOSR Minigrant Program, was to initiate work on a well-defined portion of the broader problem of developing analytical material models for an ICAM system for sheet metal forming. In particular, this work has focused on the problem of determining an appropriate constitutive equation for the two-phase (α/β) Ti-6Al-4V alloy. It was carried out in close contact with work to develop analytical forming limit curves undertaken at the Air Force Materials Laboratory by Dr. H. L. Gegel and Dr. L. J. Teutonico since the constitutive equation is needed in the forming limit curve analysis.

The Minigrant effort led to an AFML contract entitled "Determination of Constitutive Equations for High Strength Aluminum and Titanium Alloys Applicable to Sheet Metal Formability" which began in September, 1977. The work on this contract is being coordinated with a Batelle Columbus Laboratories contract on mathematical modeling of sheet metal forming funded through the AFML ICAM program. A common tensile test matrix for Ti-6Al-4V and 2024-0 aluminum has been developed to reduce duplication of effort and assure that the resulting constitutive equations will be useful in the formability and sheet metal process models.

3.0 Publications

The work reported here, plus work now in progress to fit the hardness curves to Eq. (1), will form the basis of a publication to be entitled "Mechanical Equation of State in Ti-6Al-4V." It is anticipated that this will be submitted to Scripta Metallurgica.

4.0 Personnel

In addition to the principal investigator, two students received support from this grant.

Mr. Jiinjen Sue was supported as a 1/2 time graduate assistant for the summer, 1977. Mr. Sue received the M.S. degree in Physics in December, 1977 and is now a Ph.D. candidate at Iowa State University.

Mr. John S. Leffler was supported as an undergraduate hourly employee from March to June, 1977. I would like to acknowledge his very skillful and valuable contribution in writing the automatic data acquisition system control program. Mr. Leffler expects to receive his B.S. degree in Physics in June, 1978.

5.0 Acknowledgements

I would like to thank Dr. John S. Martin and Dr. Merrill L. Andrews of the Wright State Plasma Physics Group for making the PDP-11 data acquisition system available for the duration of this Grant. I would also like to thank Dr. Harold L. Gegel, AFML/LLM, for supplying the tensile specimens and for his continuing encouragement and support.

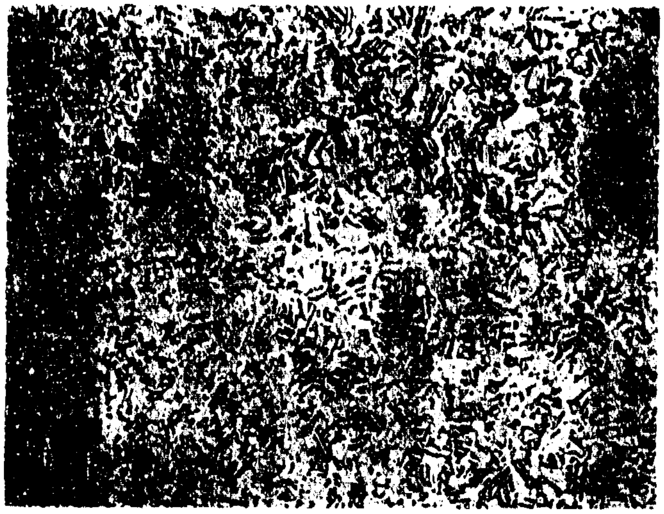


Fig. 1(a) Microstructure of annealed Ti-6Al-4V

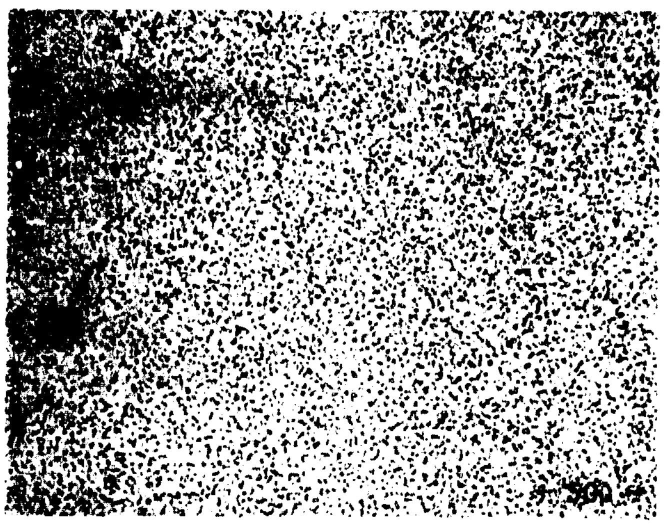
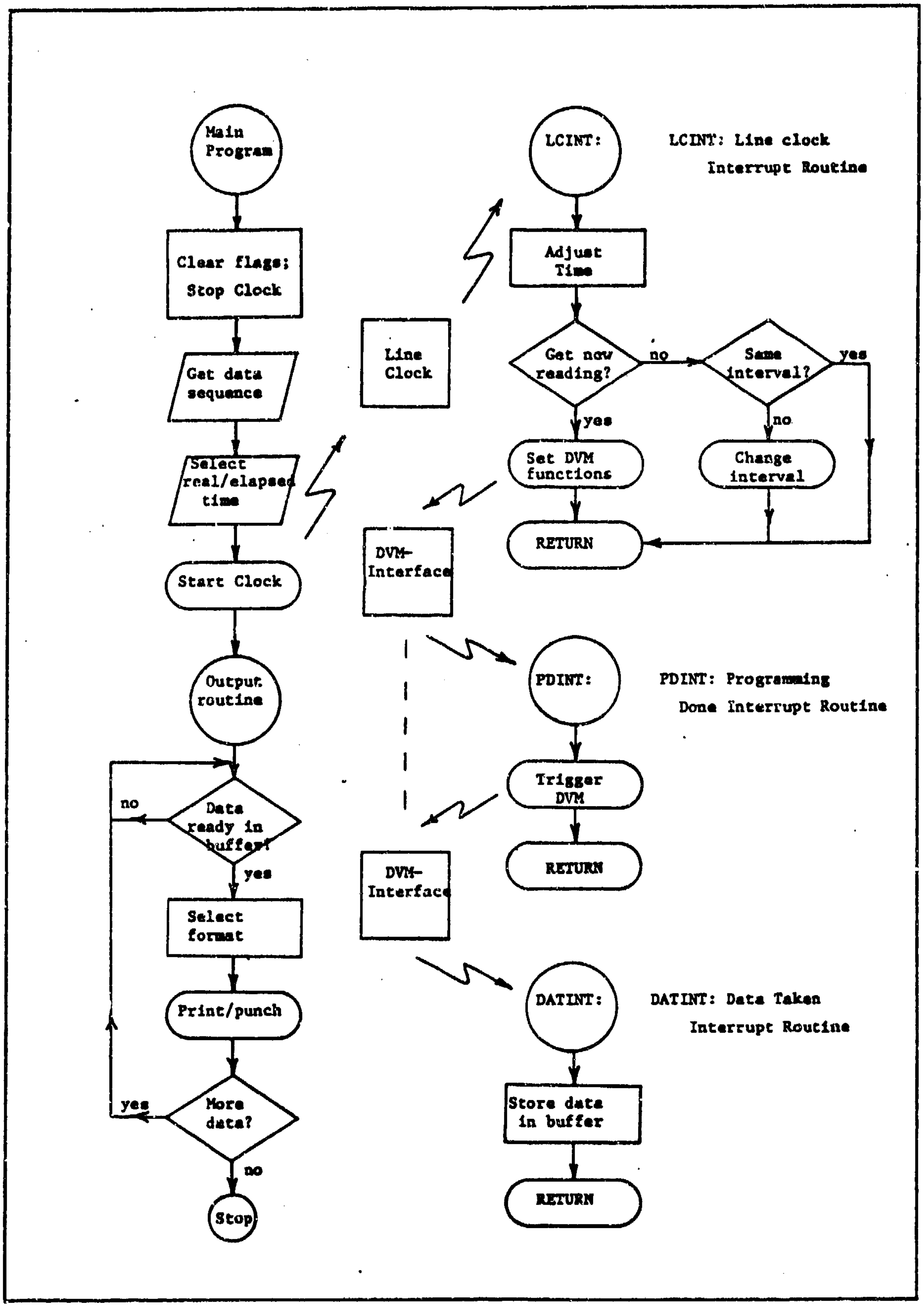


Fig. 1(b) Microstructure of annealed ELI Ti-6Al-4V



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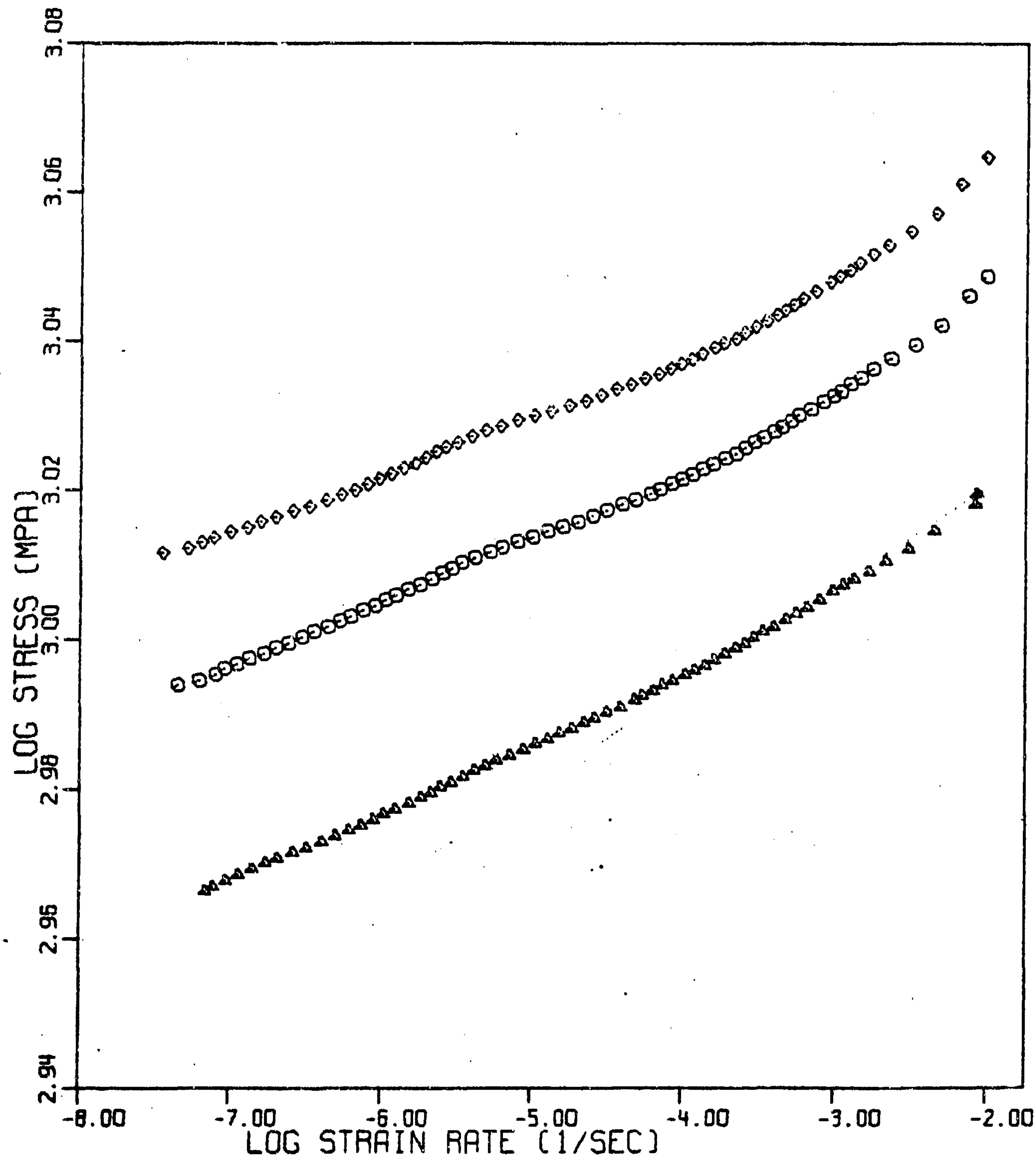
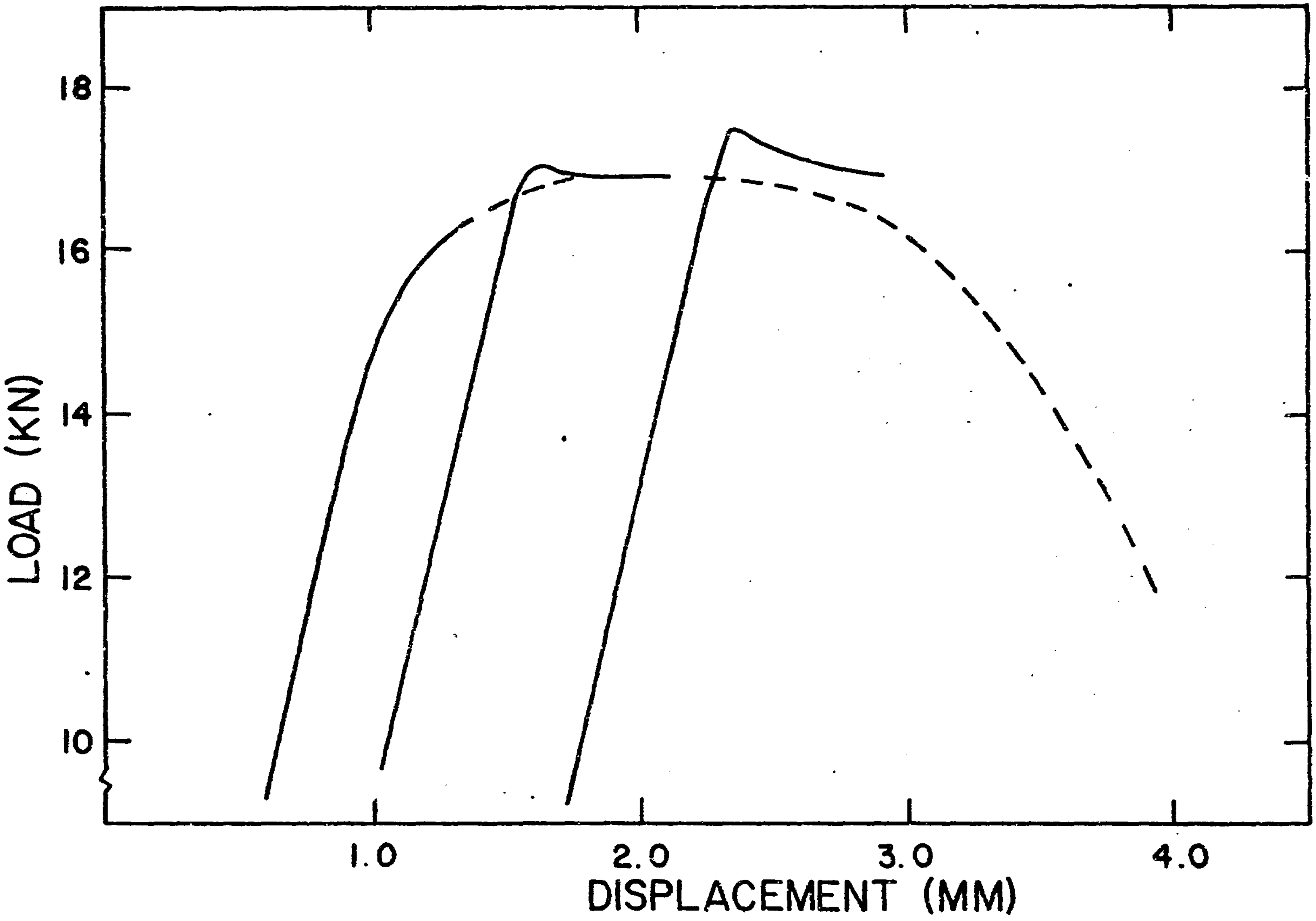


Fig. 3. Room temperature hardness curves for a standard grade Ti-6Al-4V specimen at plastic strains of .015 (▲), .051 (●), and .088 (◆).



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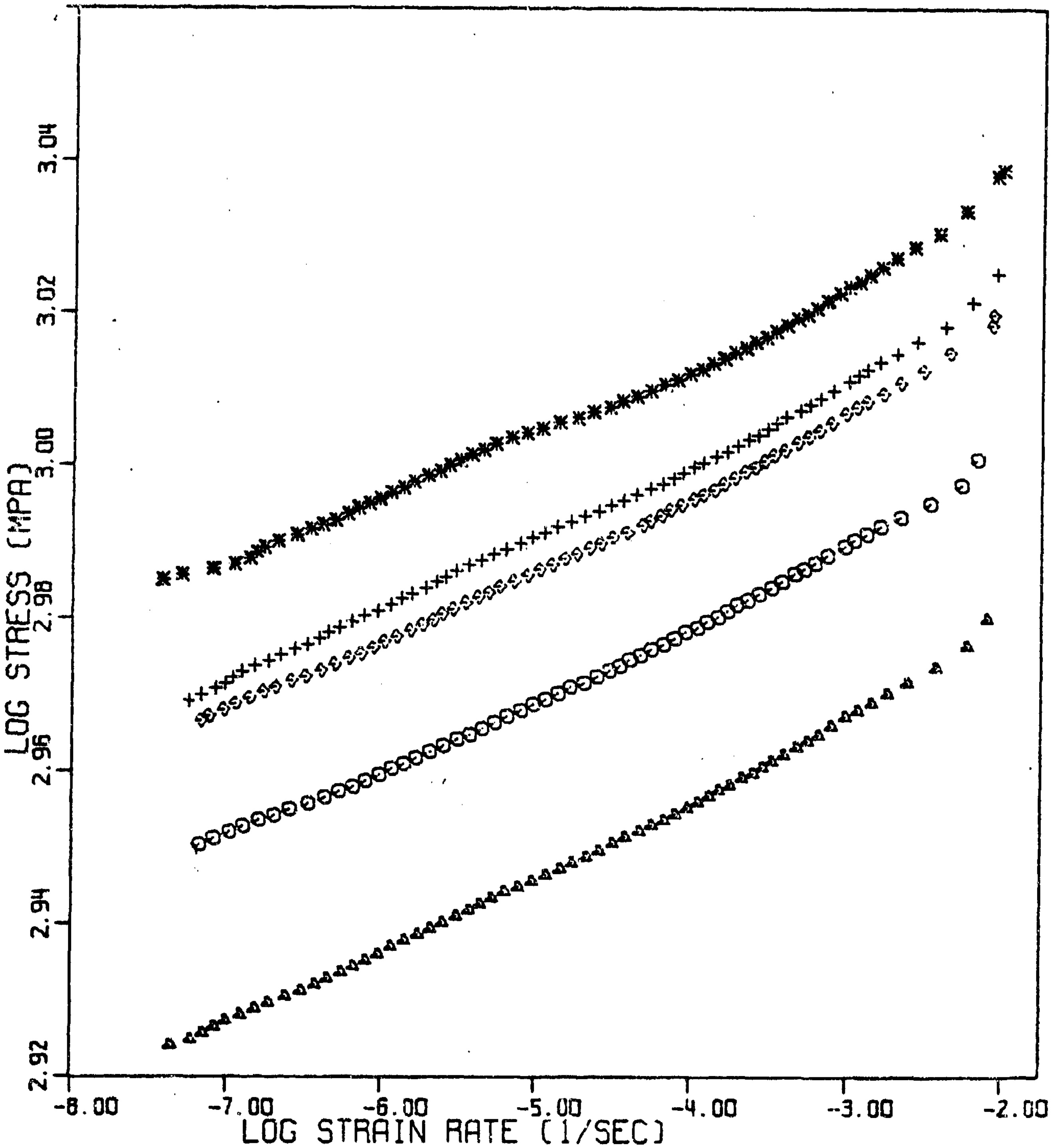

Fig. 5. Initial room temperature hardness curves for an ELI-grade specimen at a plastic strain of .013 (▲) and four standard grade specimens at strains of .007 (⊙), .015 (⊘), .018 (+), and .033 (✱).

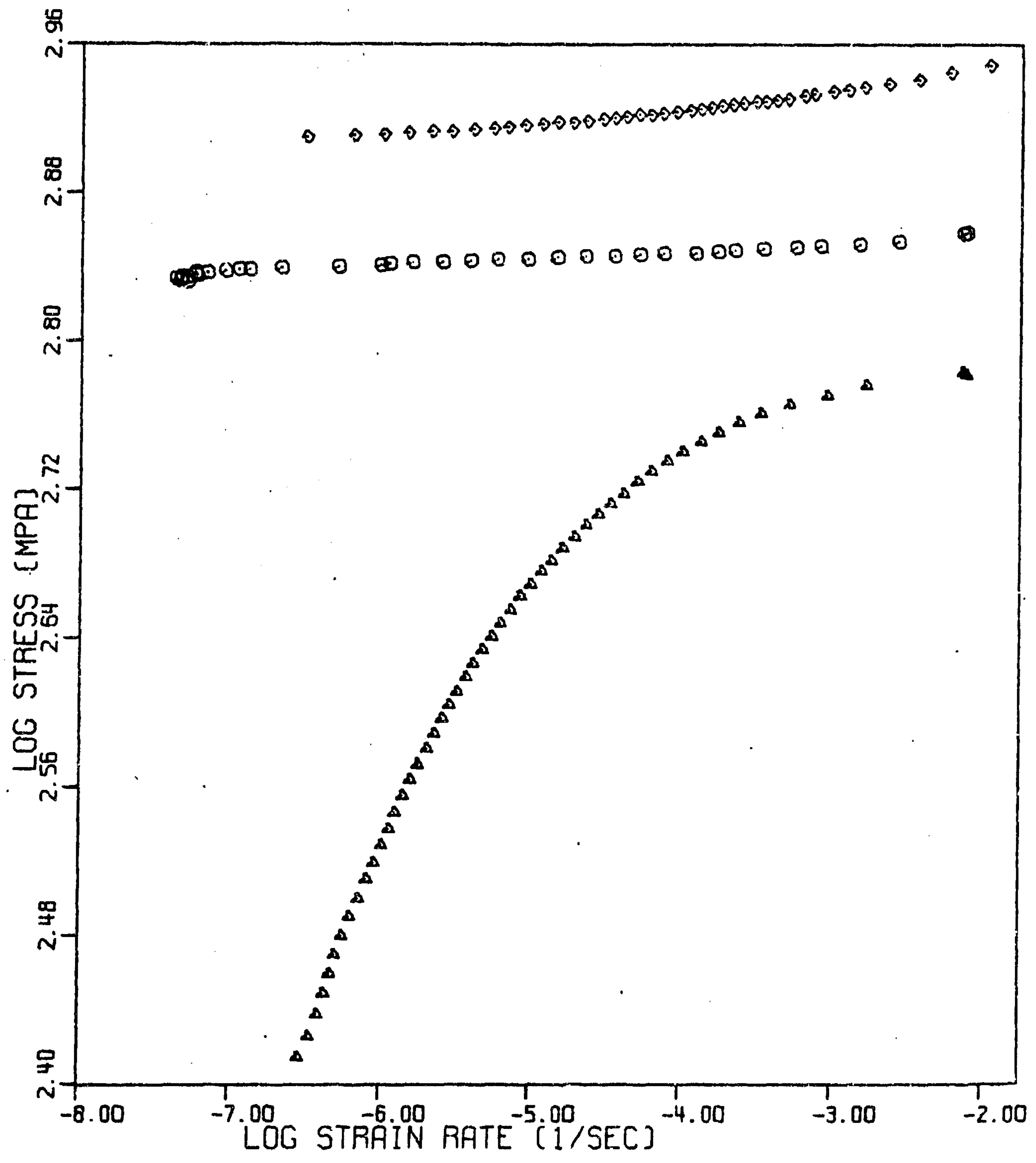

Fig. 6. Hardness curves for a single standard grade specimen at temperatures of 500°C (▲), 350°C (⊙), and 200°C (◈).

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